Final Technical Report
1434-95-G-2529

Title:	Use of Amplitude Data for Real-Time Processing
Investigator:	Hiroo Kanamori
Institution:	California Institute of Technology
Address:	Seismological Laboratory 252-21 California Institute of Technology 1200 E. California Blvd. Pasadena, California 91125
Telephone:	(626) 395-6914
E-mail address:	hiroo@gps.caltech.edu
Program Element:	IV

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number (1434-95-G-2529). The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Non-technical Summary

1434-95-G-2529

Title:	Use of Amplitude Data for Real-Time Applications
Investigator:	Hiroo Kanamori
Institution:	California Institute of Technology
Address:	Seismological Laboratory 252-21 California Institute of Technology 1200 E. California Blvd. Pasadena, California 91125
Telephone:	(626) 395-6914
E-mail address:	hiroo@gps.caltech.edu

Program Element: IV

Earthquakes are traditionally located using travel times. However, since the ground-motion amplitude generally decays with the distance from the source, it should also be possible to locate earthquakes using amplitude data. Locating earthquakes with amplitudes has its own merits: For post-earthquake emergency services, it is often more important to know the spatial distribution of strong-motion parameters such as peak acceleration and peak velocity than the rupture initiation point itself. In view of this importance, we developed a method to locate earthquakes using the amplitude data observed with digital seismic stations in Southern California. The on-line system thus developed is currently used for routine processing at the Southern California Digital Seismic Network, and is providing the basic information on the distribution of ground-motion to the public immediately after major earthquakes.

Abstract

We developed a method to locate the strong ground motion centroid (SMC) from the amplitude data observed with digital seismic stations in Southern California. The on-line program thus developed is called "Richter" and is currently used for routine processing at the Southern California Digital Seismic Network. In the program currently used, the simulated Wood-Anderson amplitude computed from broad-band and strong-motion records are used. To use this method effectively we determined the amplitude stations corrections (i.e. amplitude site amplification factors) for all the stations. The station corrections for each station are determined simultaneously with the earthquake magnitudes.

The method has been continuously modified to increase the speed and reliability of the location method. The output from this program is providing the basic information on the distribution of ground-motion in southern California immediately after major earthquakes.

Research

The method described here was developed during the period, November, 1994 to April, 1996. However, the method has been routinely applied to the data collected by Southern California Seismic Network and we report here up-to-date results which we believe are more useful than those obtained during the development stage of the project.

Program "Richter"

The program is based upon the method described in Kanamori (1993). Earthquakes are traditionally located using travel times. However, since the ground-motion amplitude generally decays with the distance from the source, it should also be possible to locate earthquakes using amplitude data. Amplitudes are affected by many factors other than the distance so that we do not expect to be able to locate the epicenter, the location of the initial rupture, very accurately with amplitude data. However, locating earthquakes with amplitudes has its own merits: For post-earthquake emergency services, it is often more important to know the spatial distribution of strong-motion parameters such as peak acceleration and peak velocity than the rupture initiation point itself. This is especially true for thrust earthquakes. The amplitudes are usually much easier to determine than the arrival times, especially for events with complex rupture patterns or with immediate foreshocks in which event association can be difficult.

In "Richter", we use the amplitude, A, of simulated Wood-Anderson records, and the following magnitude relation for southern California.

$$\log A = M + f(\Delta, \phi, \lambda) \qquad (1)$$

Here f(Δ) is the amplitude attenuation curve. We fit the observed Wood-Anderson amplitude data with equation (1) and determine M, latitude (ϕ), and longitude (λ) of the strong motion centroid (SMC). Equation (1) is nonlinear with respect to ϕ and λ. We scan the model parameter space (M, ϕ, λ) to determine the approximate location of the global minimum of the error function. Then we use the values of M, ϕ, and λ at that location as the first approximation to determine the final solution using the method of least-squares. This procedure is especially important for spotting an event located outside the network.

M_L Station Corrections

In applying this method, accurate determinations of station corrections are necessary. Since the amplitudes from the 3 components (Vertical, North-South, and East-West) are used separately, the station corrections are determined for each component as follows.

We assume that the amplitude variation with distance is given by,

$$a_{ij} = a_{0j} s_i r_{ij}^{-n} \exp(-k r_{ij}) \qquad (2)$$

where a_{ij} is the amplitude at station i (i=1, 2, 3, ···, N) for event j (j=1, 2, 3, ···, M), r_{ij} is the hypocentral distance between station i and event j, s_i is the station amplification factor for station i, and a_{0j} is the amplitude factor for event j. The constants n and k determine the amplitude attenuation function in the form $r^{-n}\exp(-kr)$. For event j, we absorb s_i in a_{ij}, and write

$$\log a_{ij} = \log a_{0j} - n \log r_{ij} + \log e(-kr_{ij}) \qquad (3)$$

and determine $\log a_{0j}$, n, and k by solving a least-square problem for (3). Then, we compute the reduced amplitude by

$$a_{ij}^{'} = a_{ij} / a_{0j} \qquad (4)$$

Having computed all $a_{ij}^{'}$ for all the events, we re-determine n and k by solving a least-square problem for

$$\log\left(a_{ij} / a_{0j}\right) = -n \log r_{ij} + \log e(-kr_{ij}) \qquad (5)$$

for the entire data set. This procedure is essentially equivalent to stacking the data for all the events with different magnitudes after normalizing the amplitudes to those with a reference magnitude.

Because of the particular functional form of (2), considerable trade-off exists between n and k. The values of n and k for each frequency band thus determined are 1.1835, and 0.00497 km^{-1}, respectively. Figure 1 shows the amplitude attenuation curve determined in this project.

M_L station corrections were determined as the average of the deviation of the amplitude at each station from the reference attenuation curve shown in Figure 1.

Figures 2, 3, and 4 show M_L station corrections for all the digital stations currently operating in southern California. Table 1 lists the numerical values. With these station corrections, we can determine the centroid accurately for most earthquakes with $M_L \geq 3.5$ in southern California. The centroid is currently used for making ShakeMap (Wald et al. 1998) which is providing key real-time ground-motion amplitude information to the public. The centroid and the attenuation relation are used to interpolate and extrapolate the observed amplitude distribution so that the resulting contour lines can represent the overall distribution correctly. Two representative examples of ShakeMap are shown in Figures 5 and 6.

Conclusion

With the use of high quality digital data, we have established a method of rapidly mapping ground motion distribution immediately after a large earthquake. This method has been implemented in the Southern California Seismic Network and is a key element of the ground motion monitoring system in Southern California.

References

Kanamori, H., Locating Earthquakes with Amplitude: Application to Real-Time Seismology, *Bull. Seismol. Soc. Am., 83*, 264-268, 1993.

Kanamori, H., Maechling, P., and E. Hauksson, Continuous monitoring of ground-motion parameters, abstract, *Seismological Research Letters*, 68, 319, 1997.

Kanamori, H., E. Hauksson, and T. Heaton, Real-time seismology and earthquake hazard mitigation, *Nature*, *390*, 461-464, 1997.

Wald, D. J., V. Quitoriano, T. J. Heaton, and H. Kanamori, 1998. Rapid generation of peak ground motion and intensity maps for earthquakes in southern California, *Earthquake Spectra* , submitted.

Table 1. M_L Station Corrections

Station	Lat.	Long.	N	ΔM_L	St. Dev.
pasbz	34.148	-118.171	116	0.229	0.242
pasbn	34.148	-118.171	118	0.110	0.249
pasbe	34.148	-118.171	118	0.075	0.250
gscbz	35.302	-116.806	98	0.111	0.268
gscbn	35.302	-116.806	98	-0.063	0.278
gscbe	35.302	-116.806	98	-0.093	0.266
pfobz	33.612	-116.459	87	0.160	0.235
pfobn	33.612	-116.459	86	0.146	0.231
pfobe	33.612	-116.459	87	0.143	0.251
sbcbz	34.441	-119.715	106	-0.139	0.217
sbcbn	34.441	-119.715	106	-0.286	0.228
sbcbe	34.441	-119.715	105	-0.293	0.231
isabz	35.663	-118.474	74	0.228	0.200
isabn	35.663	-118.474	74	0.175	0.209
isabe	35.663	-118.474	74	0.137	0.212
barbz	32.680	-116.672	111	0.052	0.249
barbn	32.680	-116.672	113	-0.012	0.255
barbe	32.680	-116.672	115	-0.077	0.273
svdbz	34.107	-117.098	119	0.105	0.223
svdbn	34.107	-117.098	116	-0.221	0.232
svdbe	34.107	-117.098	117	-0.213	0.233
mlacbz	37.630	-118.836	103	-0.383	0.270
mlacbn	37.630	-118.836	95	-0.626	0.249
mlacbe	37.630	-118.836	92	-0.601	0.240
uscbz	34.019	-118.286	112	0.035	0.220
uscbn	34.019	-118.286	110	-0.227	0.221
uscbe	34.019	-118.286	110	-0.242	0.217
neebz	34.825	-114.599	108	-0.212	0.212
neebn	34.825	-114.599	109	-0.401	0.238
neebe	34.825	-114.599	109	-0.395	0.219
vtvbz	34.561	-117.330	118	-0.019	0.254
vtvbn	34.561	-117.330	118	-0.339	0.244
vtvbe	34.561	-117.330	118	-0.409	0.243
rpvbz	33.743	-118.404	120	0.063	0.186
rpvbn	33.743	-118.404	120	-0.230	0.227
rpvbe	33.743	-118.404	120	-0.353	0.217
dgrbz	33.650	-117.009	111	0.187	0.239
dgrbn	33.650	-117.009	111	0.091	0.262
dgrbe	33.650	-117.009	111	0.083	0.227
calbbz	34.140	-118.628	71	0.085	0.248
calbbn	34.140	-118.628	71	-0.140	0.267
calbbe	34.140	-118.628	71	-0.165	0.220
smtcbz	32.949	-115.720	18	-0.075	0.177
smtcbn	32.949	-115.720	18	-0.333	0.190
smtcbe	32.949	-115.720	17	-0.380	0.198
snccbz	33.248	-119.524	112	0.393	0.204
snccbn	33.248	-119.524	117	0.232	0.221
snccbe	33.248	-119.524	115	0.174	0.232
glabz	33.051	-114.828	15	0.106	0.245
glabn	33.051	-114.828	17	0.051	0.271

glabe	33.051	-114.828	17	-0.095	0.300
cwcbz	36.440	-118.080	82	0.490	0.229
cwcbn	36.440	-118.080	95	0.320	0.221
cwcbe	36.440	-118.080	95	0.284	0.246
osibz	34.614	-118.724	100	0.130	0.191
osibn	34.614	-118.724	101	-0.019	0.216
osibe	34.614	-118.724	99	-0.028	0.208
gpobz	35.649	-117.662	53	-0.158	0.201
gpobn	35.649	-117.662	53	-0.370	0.240
gpobe	35.649	-117.662	52	-0.384	0.217
lklbz	34.616	-117.824	73	-0.114	0.215
lklbn	34.616	-117.824	71	-0.348	0.218
lklbe	34.616	-117.824	72	-0.412	0.233
mwcbz	34.224	-118.053	56	0.184	0.254
mwcbn	34.224	-118.053	53	-0.021	0.208
mwcbe	34.224	-118.053	55	0.054	0.270
sbpxbz	34.232	-117.235	69	0.261	0.193
sbpxbn	34.232	-117.235	68	-0.258	0.186
sbpxbe	34.232	-117.235	69	-0.081	0.207
shobz	35.900	-116.276	69	-0.174	0.247
shobn	35.900	-116.276	62	-0.366	0.276
shobe	35.900	-116.276	67	-0.443	0.228
sotbz	34.417	-118.449	70	-0.034	0.227
sotbn	34.417	-118.449	68	-0.435	0.196
sotbe	34.417	-118.449	69	-0.439	0.179
coobz	33.896	-118.216	67	0.008	0.194
coobn	33.896	-118.216	66	-0.468	0.193
coobe	33.896	-118.216	66	-0.459	0.190
mtpbz	35.485	-115.553	55	0.243	0.199
mtpbn	35.485	-115.553	55	0.113	0.204
mtpbe	35.485	-115.553	55	0.094	0.216
bkrbz	35.269	-116.070	70	0.037	0.221
bkrbn	35.269	-116.070	70	-0.274	0.242
bkrbe	35.269	-116.070	70	-0.261	0.196
rvrbz	33.993	-117.376	61	0.332	0.171
rvrbn	33.993	-117.376	62	0.203	0.203
rvrbe	33.993	-117.376	62	0.160	0.198
furbz	36.467	-116.864	68	0.064	0.168
furbn	36.467	-116.864	68	-0.158	0.196
furbe	36.467	-116.864	68	-0.213	0.177
jrcbz	35.982	-117.808	51	0.210	0.211
jrcbn	35.982	-117.808	49	-0.060	0.218
jrcbe	35.982	-117.808	50	-0.053	0.211
plsbz	33.795	-117.609	58	0.185	0.167
plsbn	33.795	-117.609	58	-0.282	0.206
plsbe	33.795	-117.609	58	-0.184	0.194
tinbz	37.054	-118.230	23	-0.065	0.184
tinbn	37.054	-118.230	25	-0.209	0.196
tinbe	37.054	-118.230	25	-0.253	0.174
cppbz	34.060	-117.809	56	0.020	0.180
cppbn	34.060	-117.809	56	-0.377	0.202
cppbe	34.060	-117.809	56	-0.417	0.239
edwbz	34.883	-117.991	54	0.270	0.221
edwbn	34.883	-117.991	54	0.235	0.190

edwbe	34.883	-117.991	54	0.183	0.204
tabbz	34.382	-117.682	42	0.107	0.205
tabbn	34.382	-117.682	41	-0.331	0.237
tabbe	34.382	-117.682	42	-0.236	0.206
fpcbz	35.082	-117.583	50	0.386	0.165
fpcbn	35.082	-117.583	51	0.057	0.217
fpcbe	35.082	-117.583	51	0.083	0.205
plmbz	33.354	-116.863	49	0.182	0.207
plmbn	33.354	-116.863	48	-0.139	0.207
plmbe	33.354	-116.863	49	-0.080	0.243
smsbz	34.015	-118.456	41	0.044	0.149
smsbn	34.015	-118.456	41	-0.266	0.210
smsbe	34.015	-118.456	41	-0.328	0.221
ciubz	33.446	-118.483	36	0.359	0.195
ciubn	33.446	-118.483	26	0.197	0.212
ciube	33.446	-118.483	33	0.184	0.226
phlbz	35.408	-120.546	28	0.306	0.259
phlbn	35.408	-120.546	37	0.018	0.230
phlbe	35.408	-120.546	38	-0.036	0.289
hecbz	34.829	-116.335	27	0.196	0.247
hecbn	34.829	-116.335	33	-0.033	0.307
hecbe	34.829	-116.335	33	-0.135	0.236
swsbz	32.941	-115.796	26	0.278	0.258
swsbn	32.941	-115.796	26	0.007	0.286
swsbe	32.941	-115.796	26	-0.076	0.302
bc3bz	33.655	-115.453	29	0.368	0.186
bc3bn	33.655	-115.453	29	0.124	0.194
bc3be	33.655	-115.453	29	0.141	0.200
vcsbz	34.483	-118.117	29	0.049	0.237
vcsbn	34.483	-118.117	28	-0.196	0.302
vcsbe	34.483	-118.117	29	-0.200	0.301
tovbz	34.156	-118.820	26	0.185	0.212
tovbn	34.156	-118.820	26	0.057	0.183
tovbe	34.156	-118.820	26	0.024	0.175
btpbz	34.683	-118.575	25	-0.007	0.214
btpbn	34.683	-118.575	25	-0.372	0.178
btpbe	34.683	-118.575	25	-0.367	0.228
scibz	32.980	-118.547	13	0.216	0.225
scibn	32.980	-118.547	13	-0.052	0.259
scibe	32.980	-118.547	13	-0.019	0.206
clcbz	35.816	-117.598	18	0.286	0.204
clcbn	35.816	-117.598	19	0.271	0.206
clcbe	35.816	-117.598	19	0.195	0.160
lugbz	34.366	-117.366	22	-0.029	0.165
lugbn	34.366	-117.366	22	-0.238	0.136
lugbe	34.366	-117.366	22	-0.163	0.149
devbz	33.935	-116.577	22	-0.083	0.224
devbn	33.935	-116.577	22	-0.250	0.189
devbe	33.935	-116.577	22	-0.287	0.224
mlsbz	34.005	-117.561	20	-0.029	0.238
mlsbn	34.005	-117.561	20	-0.220	0.232
mlsbe	34.005	-117.561	20	-0.236	0.254
gr2bz	34.118	-118.299	17	0.078	0.165
gr2bn	34.118	-118.299	17	-0.241	0.150

gr2be	34.118	-118.299	17	-0.250	0.183
sswbz	33.177	-115.602	16	-0.001	0.261
sswbn	33.177	-115.602	16	-0.318	0.245
sswbe	33.177	-115.602	16	-0.337	0.235
rusbz	34.050	-118.080	15	0.009	0.261
rusbn	34.050	-118.080	15	-0.345	0.223
rusbe	34.050	-118.080	15	-0.343	0.218
lrlbz	35.479	-117.682	8	0.205	0.252
lrlbn	35.479	-117.682	8	-0.051	0.170
lrlbe	35.479	-117.682	8	0.029	0.170
crnsz	33.876	-117.561	21	-0.103	0.298
crnsn	33.876	-117.561	23	-0.259	0.245
crnse	33.876	-117.561	23	-0.246	0.236
fonsz	34.100	-117.439	17	-0.070	0.170
fonsn	34.100	-117.439	19	-0.274	0.233
fonse	34.100	-117.439	19	-0.187	0.226
fulsz	33.872	-117.923	14	-0.017	0.192
fulsn	33.872	-117.923	14	-0.353	0.254
fulse	33.872	-117.923	13	-0.397	0.261
hlnsz	34.121	-117.219	15	-0.042	0.230
hlnsn	34.121	-117.219	17	-0.364	0.246
hlnse	34.121	-117.219	16	-0.300	0.254
kiksz	34.150	-118.102	11	-0.058	0.300
kiksn	34.150	-118.102	12	-0.286	0.190
kikse	34.150	-118.102	11	-0.225	0.175
levsz	34.615	-118.291	14	0.038	0.208
levsn	34.615	-118.291	18	-0.324	0.240
levse	34.615	-118.291	19	-0.229	0.264
notsz	34.229	-118.558	13	-0.063	0.203
notsn	34.229	-118.558	17	-0.579	0.252
notse	34.229	-118.558	13	-0.517	0.263
ogcsz	33.788	-117.844	14	-0.057	0.176
ogcsn	33.788	-117.844	16	-0.398	0.223
ogcse	33.788	-117.844	15	-0.367	0.186
rrssz	33.882	-117.366	19	0.083	0.261
rrssn	33.882	-117.366	26	-0.008	0.234
rrsse	33.882	-117.366	26	-0.063	0.303
sjusz	33.487	-117.681	6	-0.213	0.325
sjusn	33.487	-117.681	11	-0.284	0.299
sjuse	33.487	-117.681	14	-0.372	0.291
sansz	33.704	-117.886	7	0.105	0.277
sansn	33.704	-117.886	14	-0.433	0.292
sanse	33.704	-117.886	14	-0.363	0.210
siosz	34.293	-119.165	6	0.048	0.211
siosn	34.293	-119.165	6	-0.204	0.199
siose	34.293	-119.165	6	-0.184	0.237
agosz	34.146	-118.767	11	-0.137	0.203
agosn	34.146	-118.767	11	-0.171	0.207
agose	34.146	-118.767	12	-0.226	0.224
smvsz	34.271	-118.744	12	-0.045	0.184
smvsn	34.271	-118.744	10	-0.356	0.284
smvse	34.271	-118.744	11	-0.302	0.240
fllsz	34.397	-118.918	10	-0.044	0.183
fllsn	34.397	-118.918	14	-0.483	0.247

fllse	34.397	-118.918	14	-0.529	0.258
bvhsz	34.076	-118.396	9	-0.025	0.083
bvhsn	34.076	-118.396	7	-0.110	0.126
bvhse	34.076	-118.396	11	-0.253	0.211
cabsz	34.156	-118.641	10	0.059	0.144
cabsn	34.156	-118.641	12	-0.106	0.163
cabse	34.156	-118.641	12	-0.220	0.176
okvsn	34.397	-119.299	5	0.007	0.157
okvse	34.397	-119.299	5	-0.089	0.262
bbasz	34.196	-118.353	9	-0.003	0.098
bbasn	34.196	-118.353	9	-0.339	0.190
bbase	34.196	-118.353	9	-0.427	0.217
bbbsz	33.353	-115.732	5	0.100	0.236
bbbsn	33.353	-115.732	8	-0.337	0.320
bbbse	33.353	-115.732	7	-0.227	0.389
elcsz	32.781	-115.536	9	-0.156	0.368
grfsz	34.119	-118.300	8	0.033	0.094
grfsn	34.119	-118.300	10	-0.140	0.112
grfse	34.119	-118.300	10	-0.272	0.127
jfpsz	34.309	-118.503	6	-0.229	0.170
jfpsn	34.309	-118.503	6	-0.529	0.264
jfpse	34.309	-118.503	6	-0.504	0.252
ltrsz	34.521	-117.990	7	-0.011	0.110
ltrsn	34.521	-117.990	6	-0.267	0.158
ltrse	34.521	-117.990	10	-0.282	0.140

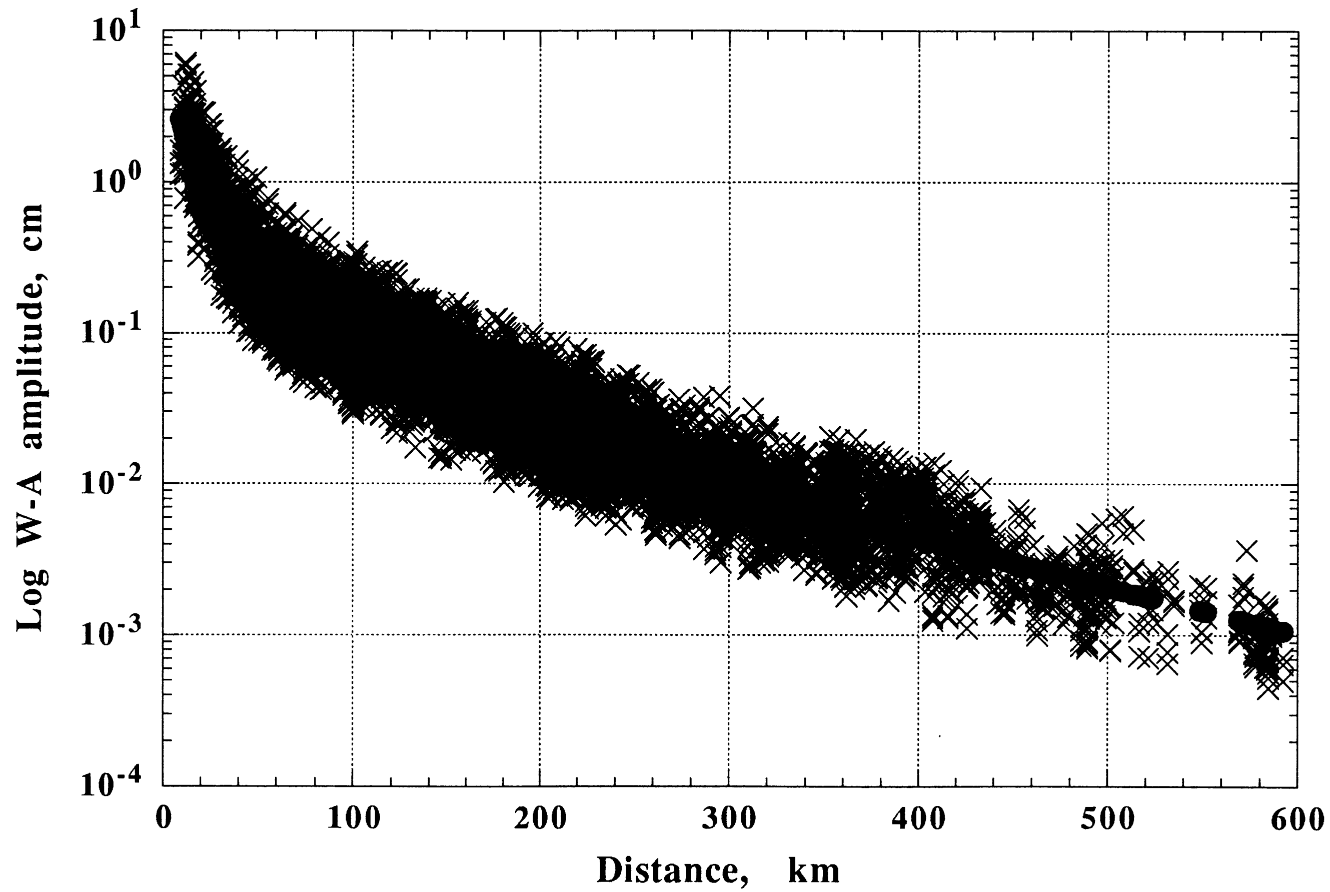

Figure 1. The attenuation curve of simulated Wood-Anderson amplitude. The amplitudes are normalized to those for a M_L=3 earthquake.

Figure 2a. M_L station corrections for the N-S component. The N-S component at the Pasadena station is used as reference, where the station correction is fixed at 0.11.

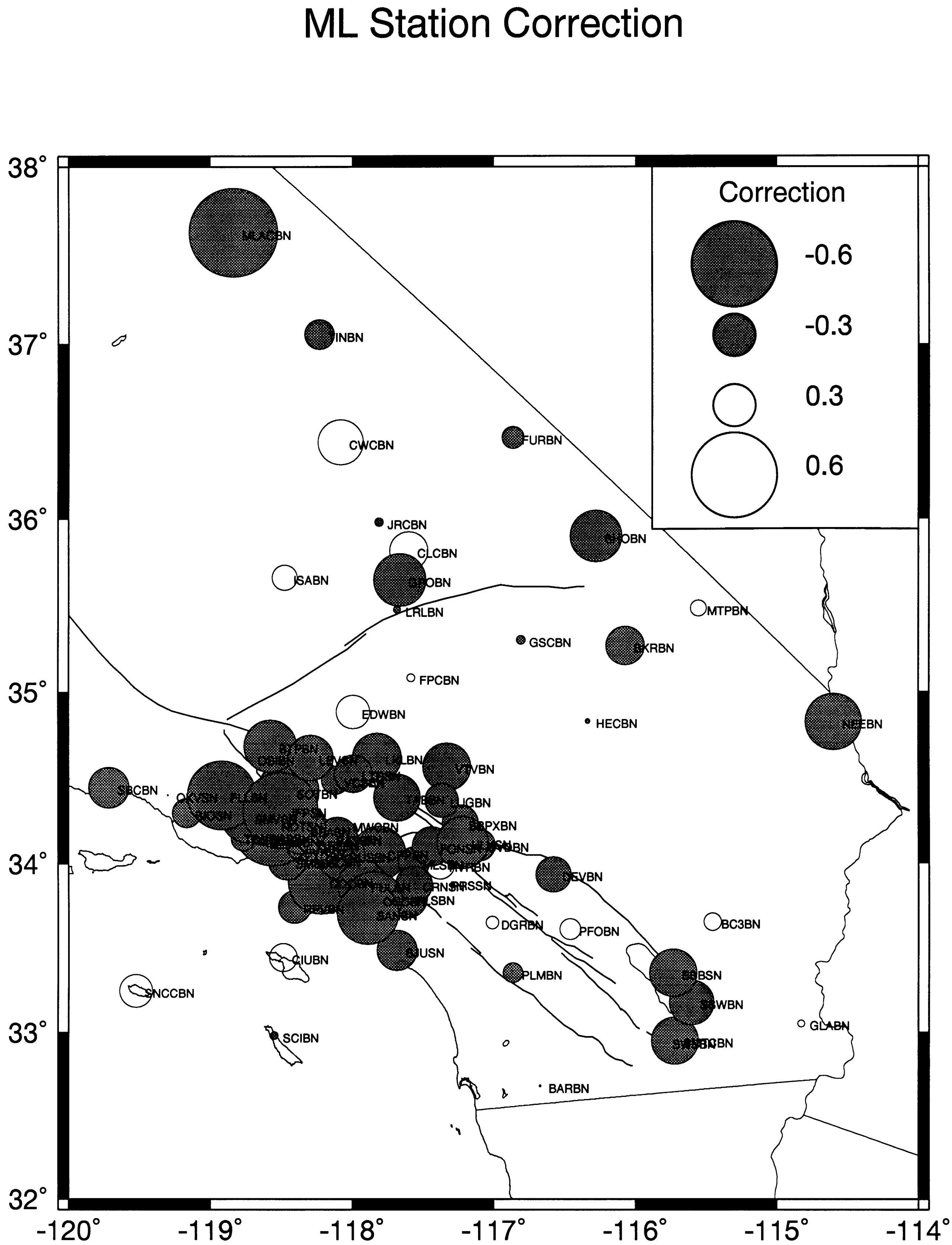

Figure 2b. M_L station corrections for the N-S component. The N-S component at the Pasadena station is used as reference, where the station correction is fixed at 0.11.

ML Station Correction

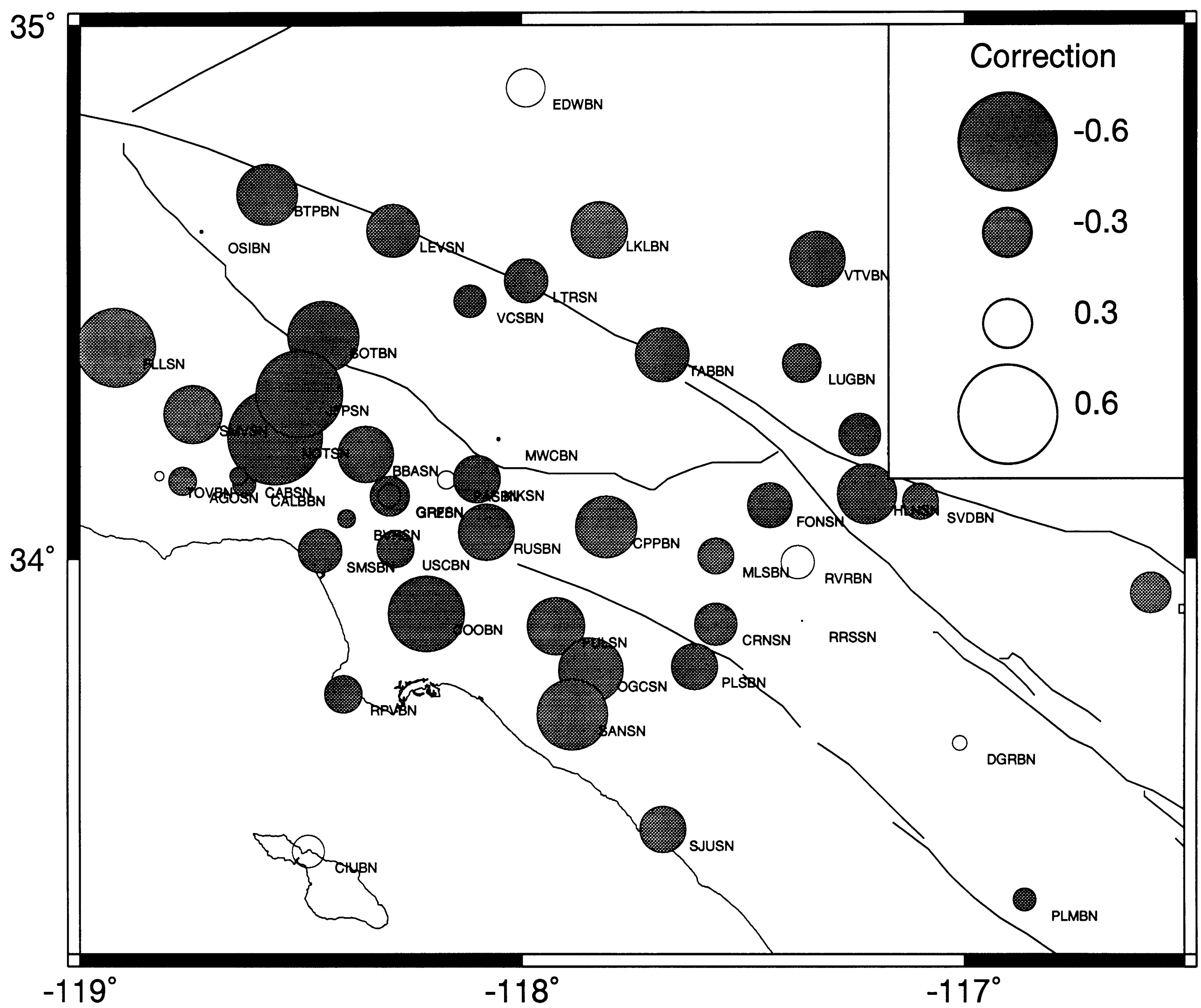

Figure 3a. M_L station corrections for the E-W component. The N-S component at the Pasadena station is used as reference, where the station correction is fixed at 0.11.

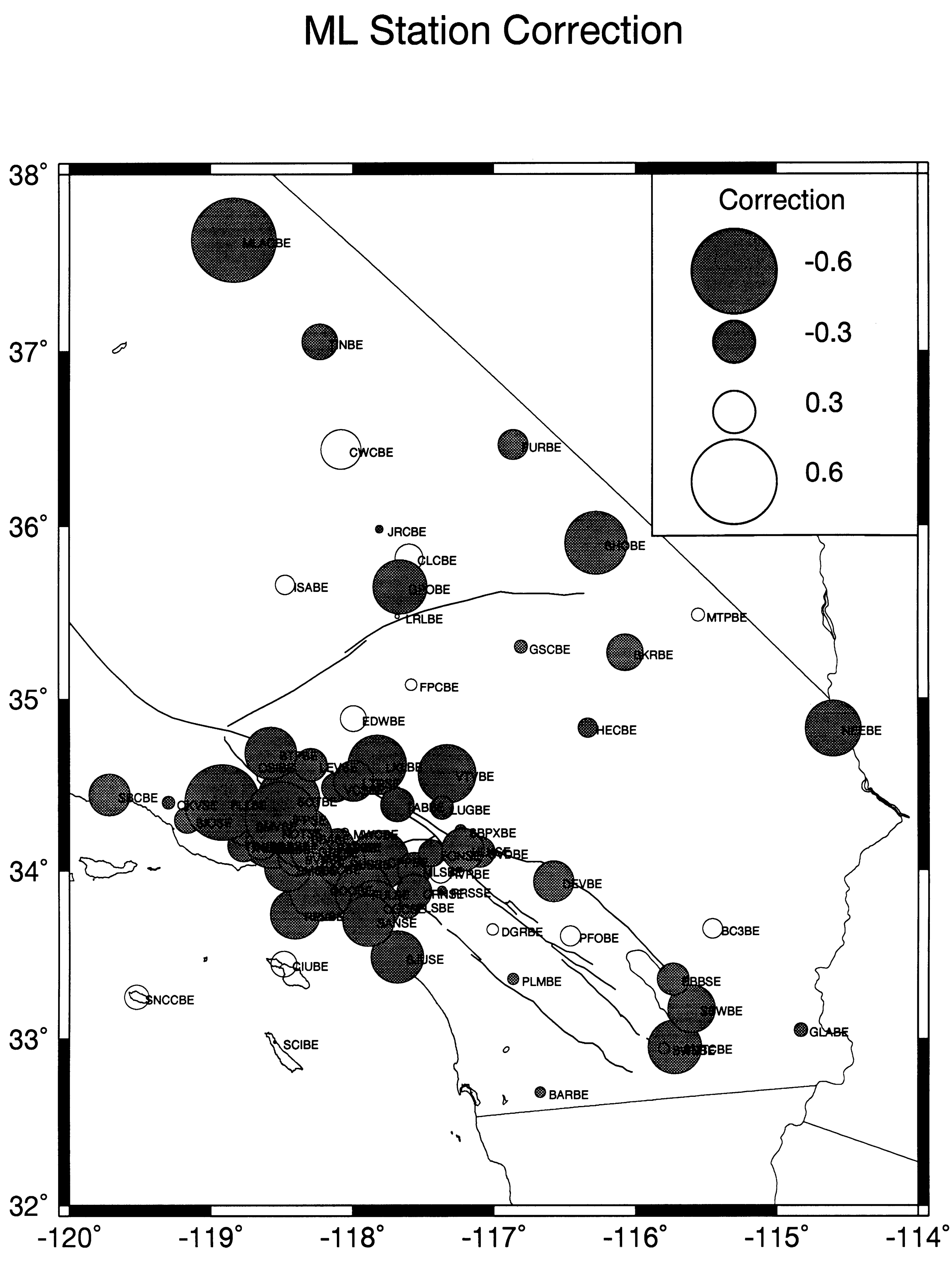

Figure 3b. M_L station corrections for the E-W component. The N-S component at the Pasadena station is used as reference, where the station correction is fixed at 0.11.

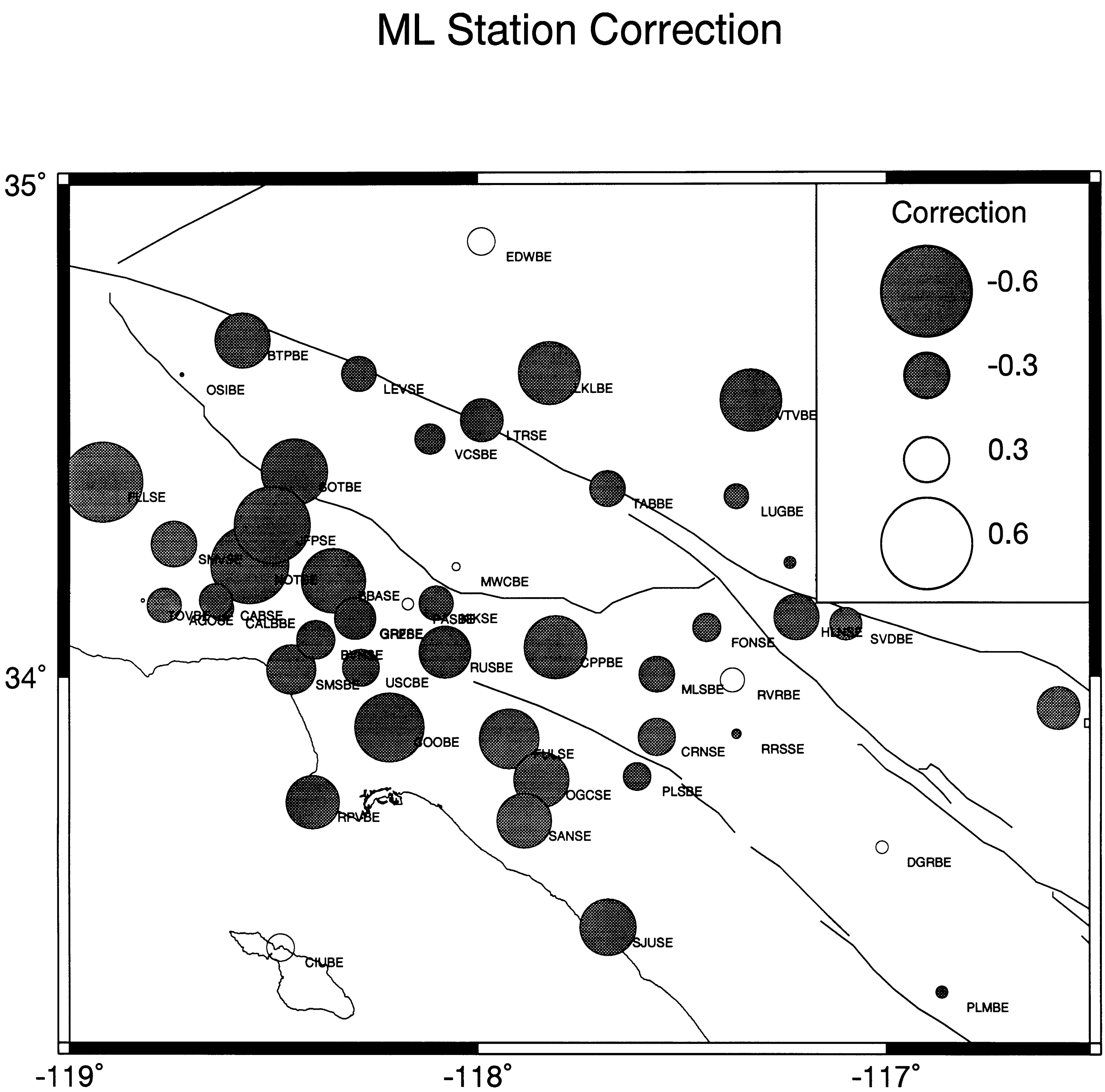

Figure 4a. M_L station corrections for the vertical component. The N-S component at the Pasadena station is used as reference, where the station correction is fixed at 0.11.

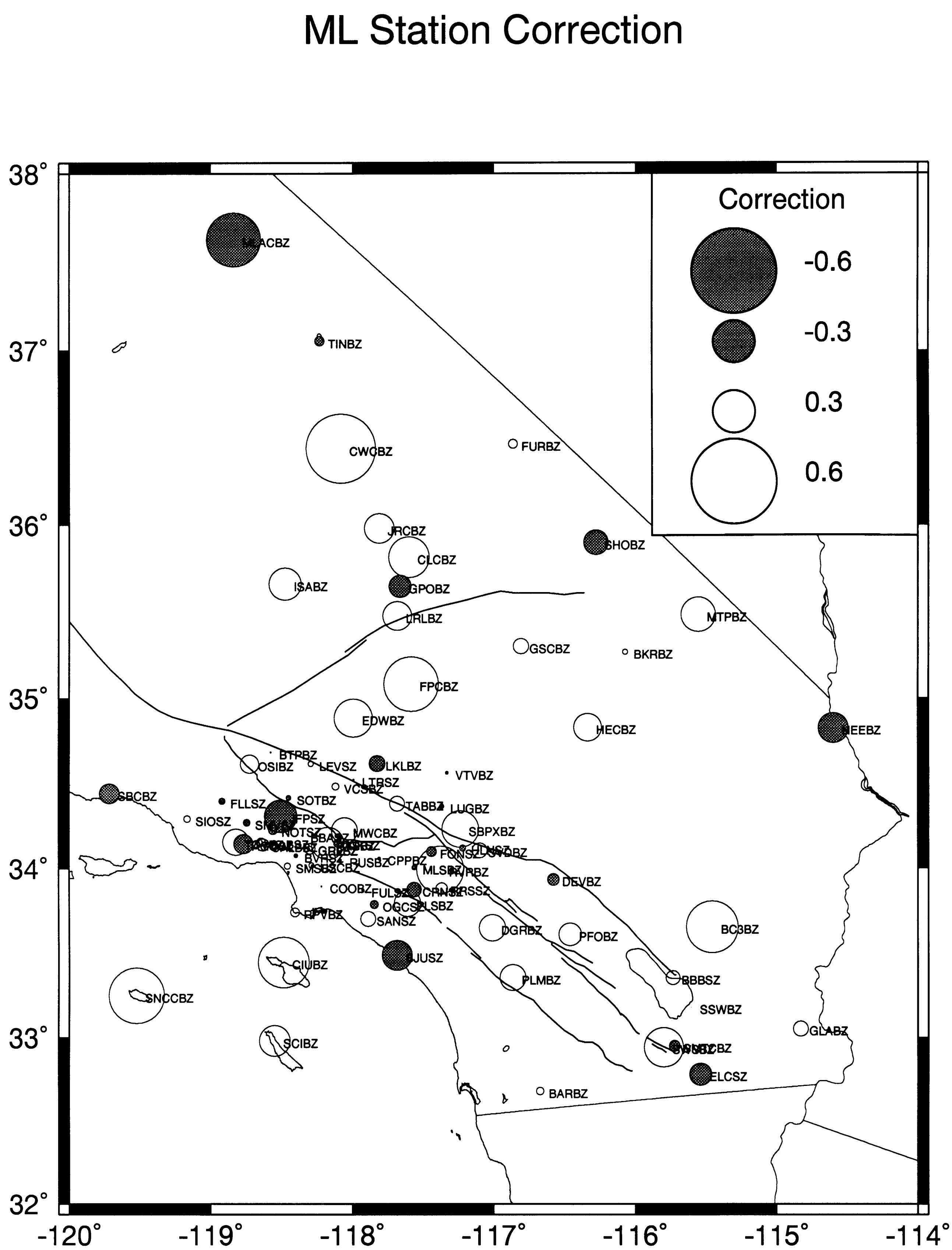

Figure 4b. M_L station corrections for the vertical component. The N-S component at the Pasadena station is used as reference, where the station correction is fixed at 0.11.

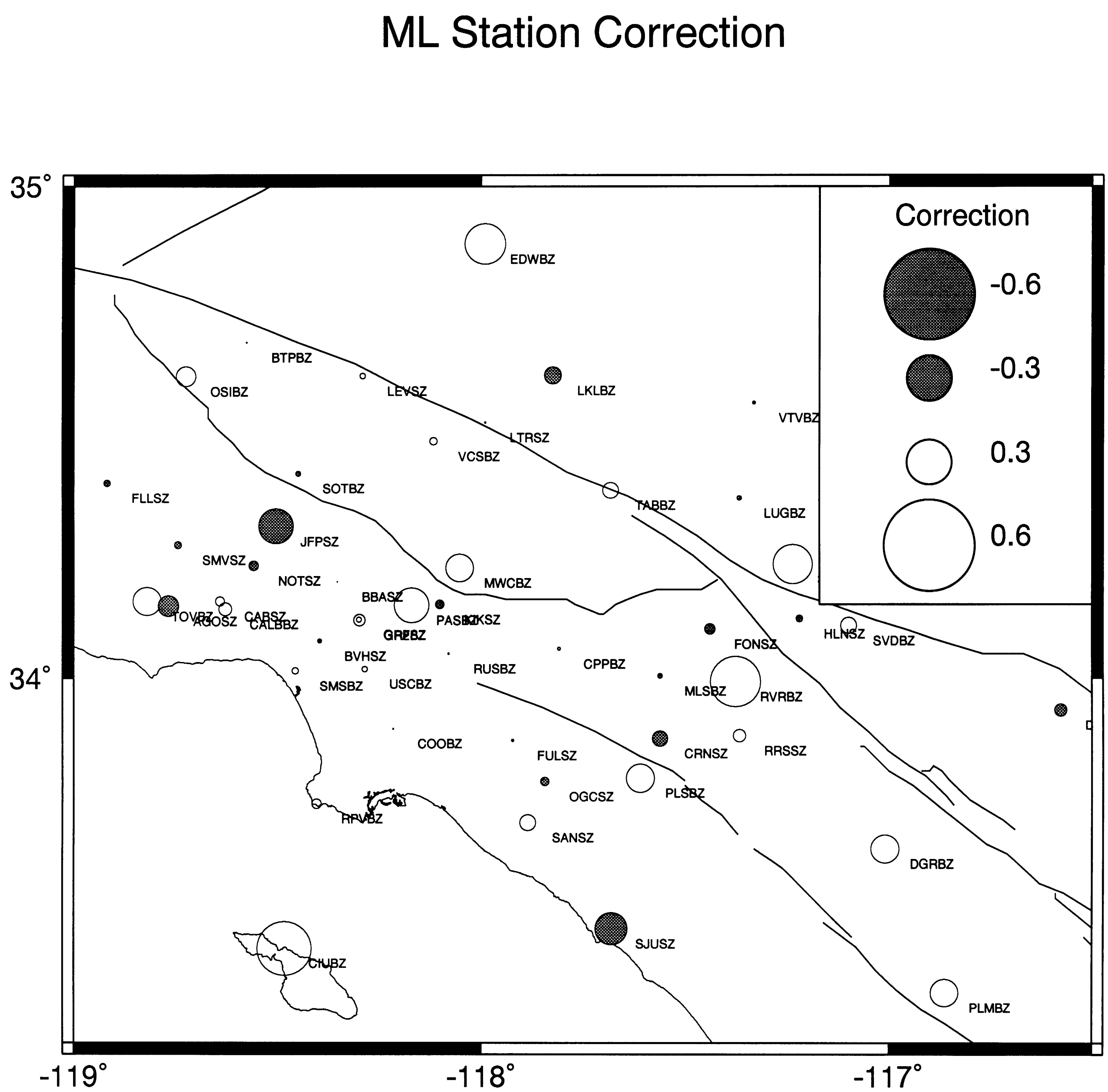

Figure 5. ShakeMap for M=4.4 earthquake on Aug. 20, 1998.

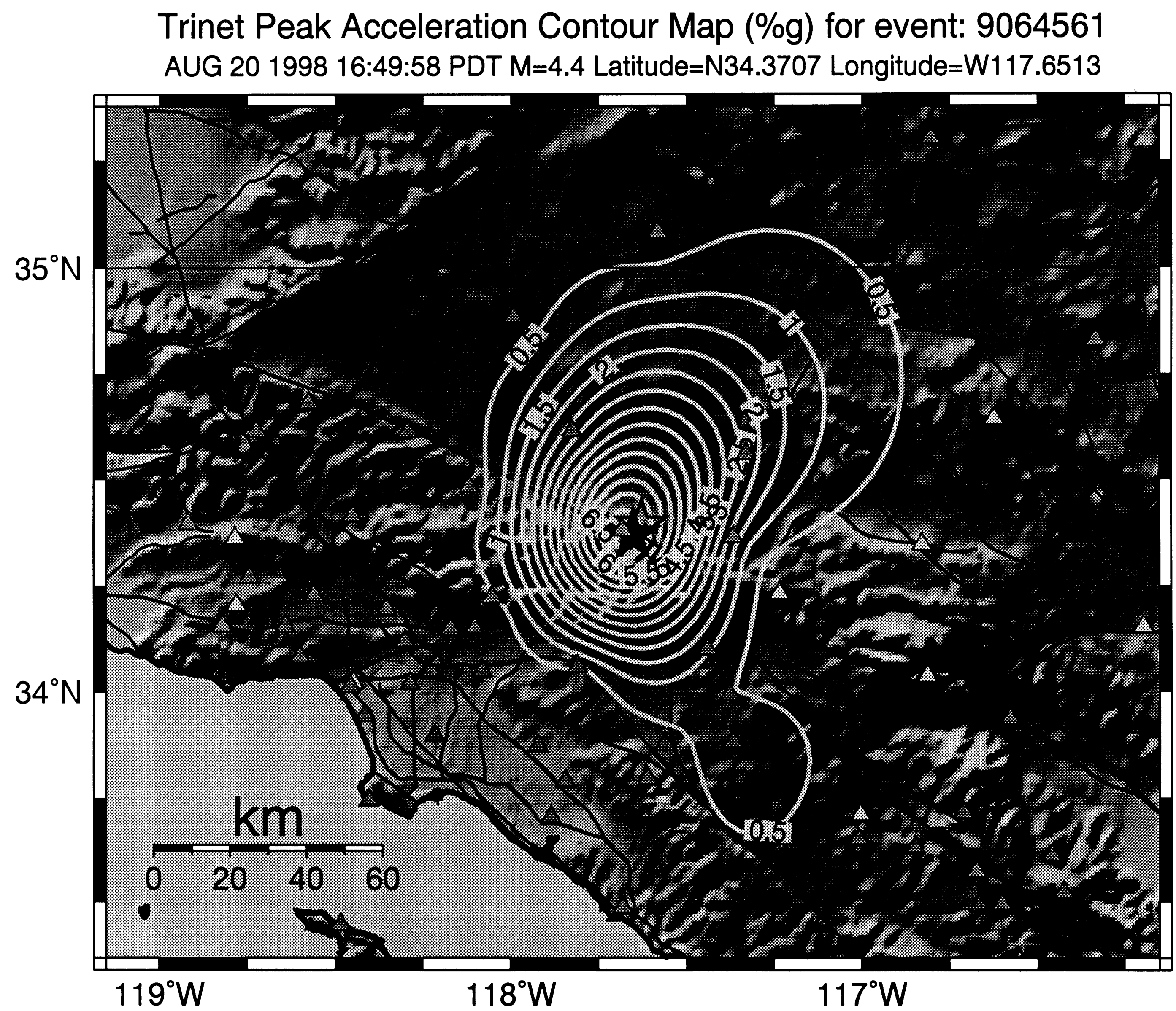

Figure 6. ShakeMap for M=4.7 earthquake on Oct. 1, 1998.